XII. *On the Polarisation of Light by oblique transmission through all Bodies, whether crystallized or uncrystallized. By* David Brewster, *LL.D. F. R. S. Edin. and F. S. A. Edin. In a Letter addressed to* Taylor Combe, *Esq. Sec. R. S.*

Read January 27, 1814.

Sir,

In a letter on "the Affections of Light in its passage through crystallized Bodies," which I had the honour of transmitting a few days ago to the Royal Society through Sir Humphry Davy, I alluded to a series of experiments which I had in view for the purpose of generalising the various phenomena which had been described. At the very commencement of this enquiry I have been led to the important general result "that "light transmitted obliquely through all transparent bodies, "whether crystallized or uncrystallized, suffers polarisation "like one of the pencils formed by doubly refracting crystals," and I hasten to communicate to you a brief sketch of the nature and consequences of this discovery.

In examining if any change was produced upon common light during its passage along the oblique depolarising axis of mica, I observed, in one position of the mineral, some appearances which indicated a partial polarisation of the incident rays. Upon turning the mica round, so as to preserve its obliquity to the incident pencil, the same phenomena presented themselves in every part of the revolution of the mica, and the quantity of polarised light was found to increase with the

obliquity of its incidence. I then substituted a plate of glass instead of the mica, and a similar result was obtained, though the quantity of polarised light was considerably less than in the first experiment. By adding one plate of glass after another, the number of polarised rays was increased by the addition of each plate, and when the plates amounted to *fifteen*, the transmitted pencil was wholly polarised at an angle of about 70° 17′, and possessed all the properties of that species of light.

When a beam of light, polarised in this manner, is viewed through a piece of agate having its laminæ parallel to the plane of refraction, the bright image of the object from which the ray proceeds will vanish, and the nebulous light will be a maximum; but if either the plates of glass or the agate is turned round, so as to bring the laminæ perpendicular to the plane of refraction, the nebulous light will vanish, and the bright image will recover its full lustre.

If we now substitute in place of the agate another series of plates, having their refracting surfaces parallel to those of the first series, and having the same inclination to the emergent ray as the first series had to the incident ray, the ray emerging from the first series will be transmitted through the second series, like ordinary light; but if the refracting surfaces are perpendicular to each other, the ray emerging from the first series will refuse to penetrate the second series, and the object from which it proceeds will be invisible.

Having thus ascertained that the pencil of light polarised by transmission comported itself, in every respect, like one of the pencils formed by double refraction, my next object was to ascertain the law of the phenomena in relation to the

number of plates and the angle of incidence at which the polarisation was effected.

For this purpose, I provided myself with forty-seven plates of crown glass, each of which was about three inches long and one broad, and having formed them successively into parcels of 47, 44, 41, 39, &c. down to eight plates, I measured by means of a theodolite the different angles at which a pencil of light was polarised when transmitted through these various parcels. The results which were thus obtained, indicated at once a regular progression, and upon comparing the number of plates with the angles, it was obvious that the number of plates were always to one another, as the cotangents of the angles of incidence at which they polarised the transmitted light; that is, if n, n' represent the number of plates in any two parcels, and φ, φ' the angles at which the pencil was polarised, we have

$$n : n' = \text{cotang. } \varphi : \text{cotang. } \varphi' \text{ and}$$
$$n \times \text{tang. } \varphi = n' \times \text{tang. } \varphi'.$$

Hence it follows that the *number of plates in any parcel multiplied by the tangent of the angle, at which it polarises light, is a constant quantity*. From a great number of observations, made with a parcel of eighteen plates, I have found the constant quantity for crown glass to be 41.84, so that we have

$$\text{tang. } \varphi = \frac{41.84}{n}$$

that is, divide the constant quantity by any given number of plates, and the quotient will be the natural tangent of the angle at which that number will polarise a pencil of light. In this way I have constructed the following table, shewing the various angles of polarisation from one plate up to

8,640,000 plates, the number by which light is polarised at an incidence of a single second.

The *first column* contains the number of plates in each parcel; the *second* the angles of incidence at which each parcel polarises the transmitted light, calculated from the preceding formula, and extending to parcels below eight, and above forty-seven, which could not easily be made the subject of experiment; the *third* column contains the experimental results from which the law was deduced; and the *fourth* exhibits the differences between the calculated and observed angles. The differences are all within the limits of error, and are singularly small when we consider the difficulty of observing the complete extinction of a luminous object, when the light by which it is formed has traversed a great number of plates. When the angle of incidence exceeds the angles of polarisation contained in the table, the pencil of light still emerges in a polarised state.

TABLE *shewing the Angles at which Light is polarised by oblique Refraction, through different numbers of Plates.*

Number of Plates in each Parcel.	Angles of Incidence at which Light is polarised. By Calculation.	Angles of Incidence at which Light is polarised. By Experiment.	Differences between the calculated and observed Angles.
1	88° 38′		
2	87 16		
3	85 54		
4	84 32		
6	81 50		
8	79 11	78° 52′ *	0 19′ −
10	76 33	76 24	0 9 −
12	74 0	74 2	0 2 +
14	71 30	72 15	0 45 +
16	69 4	69 40	0 36 +
18	66 43	66 43	0 0
21	63 21	63 39	0 18 +
24	60 8	61 0	0 52 +
27	57 10	56 58	0 12 −
29	55 16	54 50	0 26 −
31	53 28	53 16	0 12 −
33	51 44	51 0	0 44 −
35	50 5	50 23	0 18 +
39	47 1	46 50	0 11 −
41	45 35	45 49	0 14 +
44	43 34	44 0	0 26 +
47	41 41	42 0	0 19 +
100	22 42		
200	11 49		
500	4 47		
1000	2 24		
2000	1 12		
4000	0 36		
14000	0 1		
8,640,000	0 0 1″		

* This result was obtained by a parcel of plates of parallel glass.

By means of the preceding table, we may readily determine the quantity of light that is polarised at any angle φ, by a given number of plates n. Let m be the number of plates necessary to polarise the whole of the transmitted light, as found either from the table, or from the formula

$$m = \frac{41.84}{\text{tang.}\ \varphi}$$

L the quantity of light transmitted through the plates n, then

$$m : n = \text{L} : \frac{n\text{L}}{m}$$

the quantity of light required. If $\varphi = 43^\circ\ 33'$; $\text{L} = 1$ $n = 2$ and $m = 44$, then we shall have $\frac{n\text{L}}{m} = 0.04545$ the quantity of light polarised by two plates at an angle of $43^\circ\ 33'$.

The law of polarisation being thus ascertained, my next object was to determine the law of the variations which the angles experienced by changing the refractive power of the plates. From the difficulty of procuring ground plates of any substance of a high refractive power, I have made this experiment only in a rude manner with a parcel of twelve plates of green glass, which is nearly equal to flint glass in refractive power. The result of this experiment indicated that as the refractive power increased, the transmitted light was polarised at a less angle of incidence; but I cannot yet state the precise law till I have performed a series of experiments with a parcel of plates of flint glass which I am now preparing.

If a series of plates of glass is employed in the experiments on the elliptical coloured rings produced by topaz, either in polarising the incident rays in place of the reflecting plane, or in examining the rings in place of the agate and Iceland spar, the phenomena retain the same character; but are more distinct and

brilliant. The indistinctness occasioned by the interference of the two images in the case of Iceland spar, and of the bright and nebulous light in the case of the agate, is here in a great measure avoided.

The polarisation of light for this class of experiments may be effected in a very beautiful manner, by introducing into a glass trough about two-tenths of an inch wide, the fragments of a globe of glass blown to the utmost thinness, or the elementary films of which mica is composed. I have produced the same effect by coats of grease, by thick plates of mica,* by folds of gold beaters' skin,† and even by gold leaf itself. The gold beaters' skin is particularly fitted for this experiment when a strong light is used, as it disperses and equalises the light, and thus exhibits the rings to peculiar advantage.

Owing to the reflection which takes place at the surface of each plate, the image of a luminous object seen through a parcel of fifteen plates is encircled with a great number of faint images, which exhibit new phenomena. When the plates are placed at a little distance from each other in a wooden trough ABDC, Pl. VIII., fig. 1, a luminous object at O will be seen by the eye at E in the direction EE′, encircled with these faint images. By turning the trough round D, in the direc-

* The following measures were taken with two thick pieces of mica.

	Thickness.	Angle of Polarisation.
Mica - -	0.127 inch - -	63° 0′
Ditto, another specimen	0.093 - -	71 45

† The angle at which the complete polarisation of the transmitted light is effected may, in some instances, be employed as a good measure of the refractive power of the polarising plates or films. In the case of gold beaters' skin, and other substances which neither reflect nor refract light regularly, it is the only method which can be put in practice.

tion CAB, so as to increase the obliquity of the light radiating from O, the corner A will conceal the bright image at O, while the faint secondary images continue visible. If we now examine these images with a prism of Iceland spar, they will be found to be polarised exactly like the bright image; but upon increasing the obliquity of the incident rays still more, a *nebulous* light makes its appearance in the place of the faint images, and what is very singular, *this nebulous light is polarised in the opposite manner from the bright image, and the bright image has the same relation to this nebulous light, as the bright image has to the nebulous image of the agate, or as the first pencil has to the second pencil formed by doubly refracting crystals.*

When a beam of light from a candle is transmitted through a convex lens, and falls upon a series of plates at a considerable angle of incidence, a bright image A, and a row of faint images *cd* are distinctly visible, as in fig. 2. If we now view these images through a prism of Iceland spar, they will all be doubled; but upon turning round the prism, the image A will vanish, and along with it the faint images *ef*, and after another quarter of a revolution the image B will vanish, and along with it the faint images *cd*, the images A, and *ef* having reappeared. When the angle of incidence, however, is greatly increased, the secondary images *cd* always vanish along with their principal image A, and *ef* along with their principal image B.

The polarisation of the nebulous light, in an opposite manner from the bright image, first shewed itself to me in a very curious phenomenon. When the nebulous light and the bright image were both visible at the same time, and were transmitted through topaz, so as to form the elliptical coloured

rings, I was surprised to observe the lower half of all the rings completely different from the upper half, like the sketch in fig. 3, the half of the rings above the conjugate diameter of each was the very same as the *first set* described in my former paper, while the other half below the conjugate diameter contained the complementary rings, such as those which form the *second set* in the same paper.

When we polarise a beam of light by refraction, at the same angle at which it is polarised by reflection, we obtain very interesting results. The number of plates necessary for this purpose is thirty, as represented by ABCD, fig. 4. If a ray of light RS is incident at S, so that the angle of incidence is 54° 35′, then, according to the observations of Malus, the reflected ray ST will be wholly polarised, while according to the preceding experiments, the transmitted beam EF will also be completely polarised. The pencil EF, however, is polarised in the opposite manner to ST, and the two pencils have the same relation to each other, as the two images formed by double refraction. If we, therefore, suppose the thickness AC of the thirty plates diminished to such a degree, that the eye could receive both the pencils ST and EF, and if we examine these two images by a prism of Iceland spar, they will comport themselves in every respect, as if they had been produced by a doubly refracting crystal, vanishing and reappearing alternately in every quadrant of the circular motion of the spar.

As a portion of the transmitted beam SEF is polarised at its emergence from each plate, and as this portion possesses a polarisation opposite to that of the reflected beam ST, and falls upon the subjacent plates at an angle of 54° 35′, *not one particle of it will suffer reflection, but each minute portion of light*

polarised by every successive plate will force its way through all the remaining plates, and will reach the eye at E, without having lost a single ray by reflection, the light reflected at each surface being taken from the unpolarised portion of the transmitted light. Hence it follows, that the light which penetrates through a parcel of plates is not a maximum when it falls with a perpendicular incidence; that the principle employed by Bouguer for computing the intensity of the light transmitted by several plates is completely erroneous; and that the method adopted by the same distinguished philosopher for measuring the absorption of light is affected with a similar error.*

The celebrated discovery made by Malus, of the polarisation of light by oblique reflection, is perhaps the most important that optics has received since the discovery of the principle of the achromatic telescope; but though it developed a new set of phenomena, analogous to those produced by doubly refracting crystals, yet as the polarisation of one of the images, at least, formed by these crystals, was effected by *refraction*, and not by *reflection*, it did not furnish us with any information respecting the manner in which they polarised the transmitted light. The discovery, however, of the polarisation of light by oblique refraction, forms the connecting link between these two classes of facts, and holds out the prospect of obtaining a direct explanation of the leading phenomena of double refraction.

* In estimating the quantity of light absorbed, Bouguer (*Traité d'Optique sur la gradation de la Lumiere*, p. 156—160,) compared the quantity transmitted by four pieces of glass with the quantity transmitted by one piece having the same thickness with all the four. The pencil of light was incident at an angle of 15°, and hence the 177th part of the light transmitted by each plate was polarised, and therefore not altogether subject to the general law of reflection.

If two separate sets of polarising plates are placed before two luminous objects, in such a manner that their planes of refraction are perpendicular to each other, and that the rays are incident upon both parcels at the polarising angle belonging to each, the observer will perceive two images which have all the properties of those formed by doubly refracting crystals; and in so far as the polarisation of the two pencils is concerned, the two parcels of plates form an *artificial polarising crystal*. For if these two images are viewed through a prism of Iceland spar, they will be converted into four images, and by turning round either the spar, or the plates, two of the images will vanish and reappear in every quarter of a revolution.

From these observations, we are entitled to conclude, that the mystery of the polarisation of the two pencils formed by double refraction is completely removed by a reference to a more general principle, and that the formation of two images and the oblique refraction at a perpendicular incidence are the only parts of the problem which now require a solution.

From the view which has just been given of the nature and consequences of the polarisation of light by oblique refraction, you will readily see that the prosecution of these experiments will lead to results of still higher interest. The establishment of a new law must at all times be considered as an important step in the progress of science, but when this law presides over a class of facts, all of which are unexplained, and many of which still remain to be discovered, it claims a higher regard both as an instrument of discovery, and as a principle for explaining new and analogous phenomena.

If this paper shall meet with your approbation, and that of

the Royal Society, I shall communicate to you the results of a set of experiments on the *Polarisation of Light by reflection.* In this paper I shall be able to shew, by the most satisfactory details, that the principle discovered by MALUS is not, as has been supposed, a general law, but that it depends upon a circumstance which he appears to have completely overlooked, viz. the relation between the quantities of reflected and transmitted light when the pencil is incident at the polarising angle. When light is polarised by reflection from water, the reflected light is only $\frac{41}{1000}$ part of the incident pencil, and in the case of glass it is only $\frac{75}{1000}$, but when *realgar*, *diamond*, and *chromate of lead* are employed, the light reflected at the polarising angle is above $\frac{500}{1000}$, and therefore none of these bodies have the power of polarising the whole of the reflected pencil.

I have the honour to be,

Sir, your most obedient humble servant,

DAVID BREWSTER.

Edinburgh, Nov. 24, 1813.

To TAYLOR COMBE, Esq. Sec. R. S.

Fig. 1.

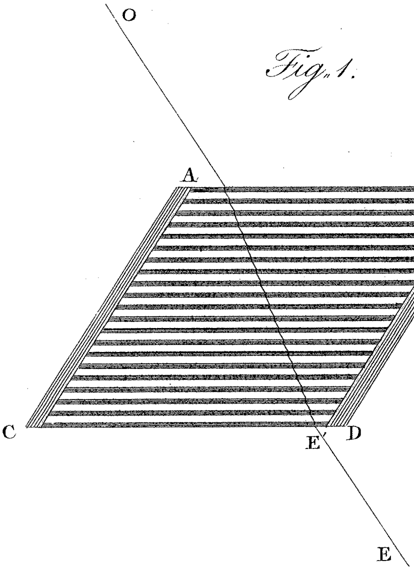


Fig. 2.

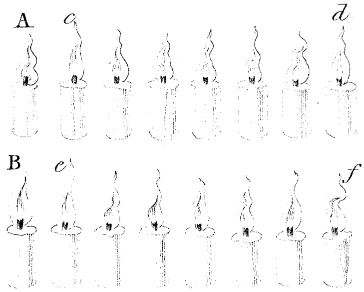


Fig. 3.

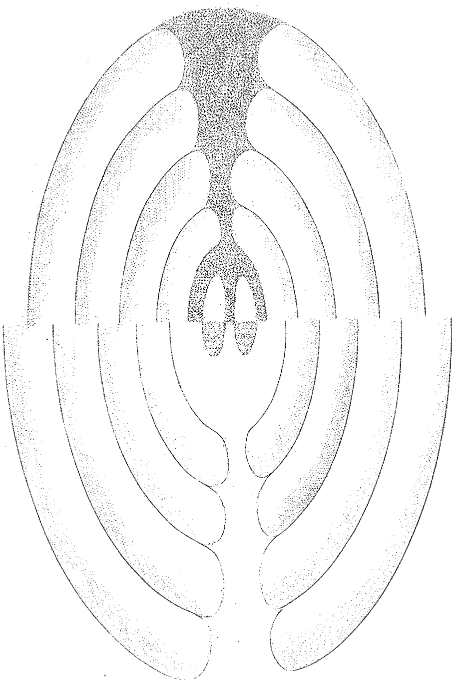
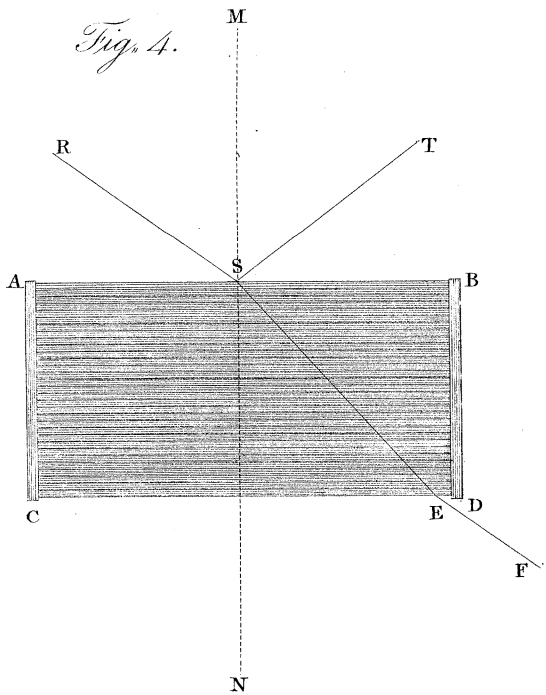


Fig. 4.



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